Physics of Particle Detectors

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Undergraduate Lecture Series

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The official schedule is maintained at:

http://ed.fnal.gov/interns/lectures/

The pictures Elliott takes will be posted on Facebook:

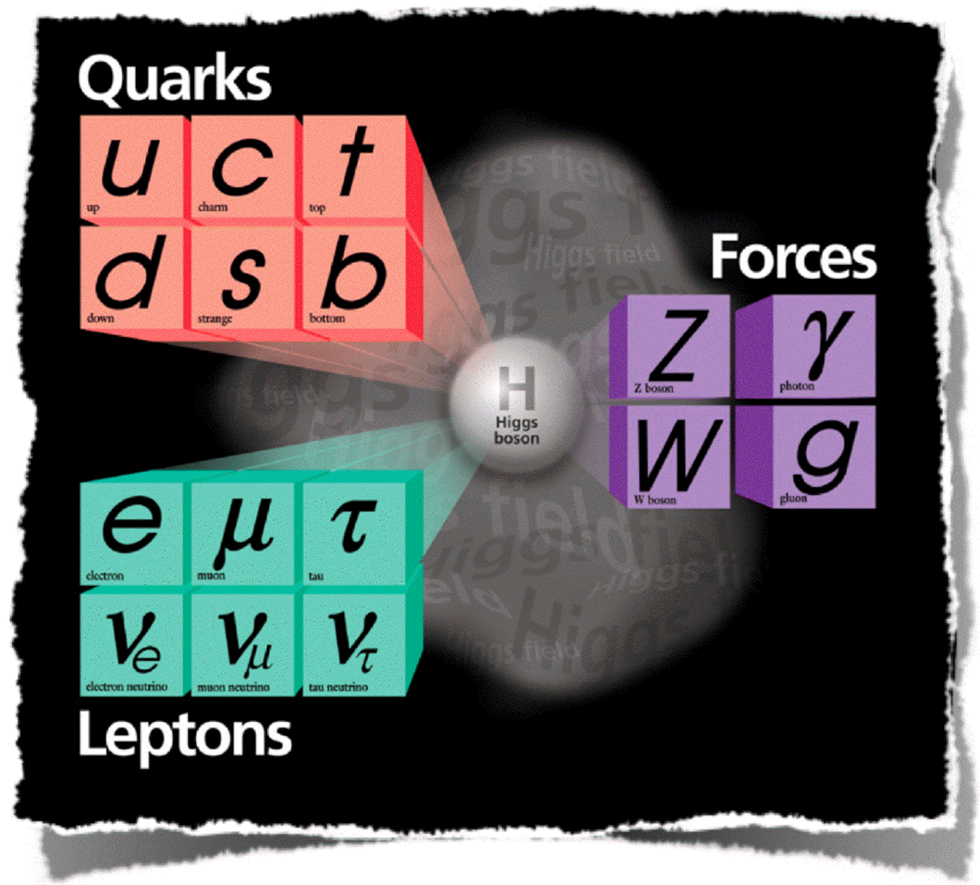
https://www.facebook.com/**fermilabsist/**

Outline

- What are we interested in seeing?
  - Strong interactions
  - Weak
  - EM
  - What particles do we see
- How do we detect these?
  - Mostly just put something in path of a particle, see what it does
    - Some slow down, some just let it pass through
  - Physics principles
  - Detector technologies
- Full experiment
- Further reading

What do we know about?

- **Full Intro Lecture on 6/13**
- Standard Model
  - Matter is made of quarks and leptons
  - Interactions are mediated by gauge bosons
- For detectors we care about:
  - Strong Interactions
  - EM Interactions
- Most commonly detected: $e^{+/-}$, $mu^{+/-}$, $pi^{+/-}$, protons, neutrons, gamma, K0, $K^{+/-}$



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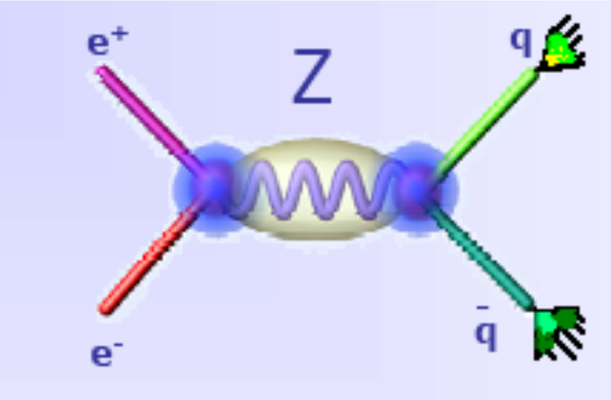
What theory tells us

- Theory tells us that an electron and a positron interact via a Z boson and produce a quark-anitquark pair



$$e^+ + e^- \rightarrow Z^0 \rightarrow q\bar{q}$$
$$(+\,\text{hadronization})$$

- Experimentally: we can send a beam of positrons and electrons towards each other and detect the end products
  - We must understand what our detectors are telling us in order to make sense of the theory
  - Properties: charge, mass, momentum, energy, etc

Particle Interactions

- Electromagnetic interactions
  - Scintillation (excitation)
  - Ionization
  - Cherenkov radiation
  - Transition radiation
  - Bremsstrahlung
  - Pair production
- Strong interactions
  - Hadronic showers

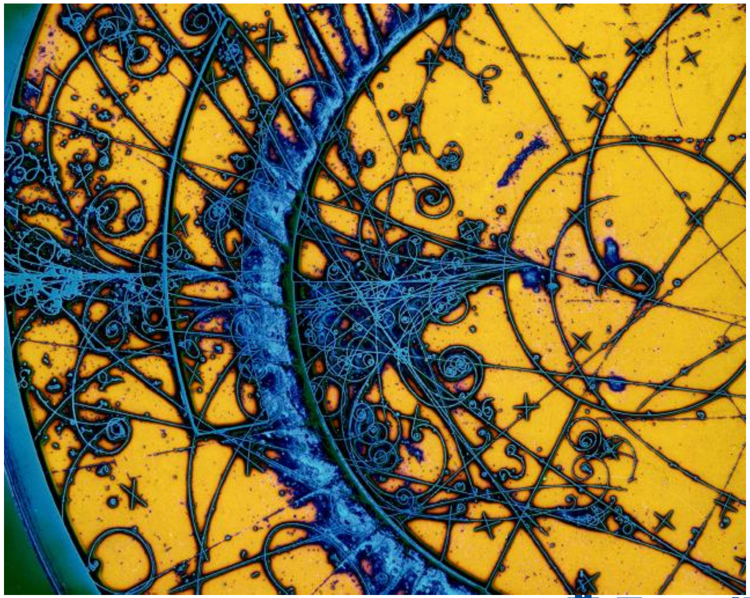
Tracking Detectors

Cherenkov/TRD

Calorimeters

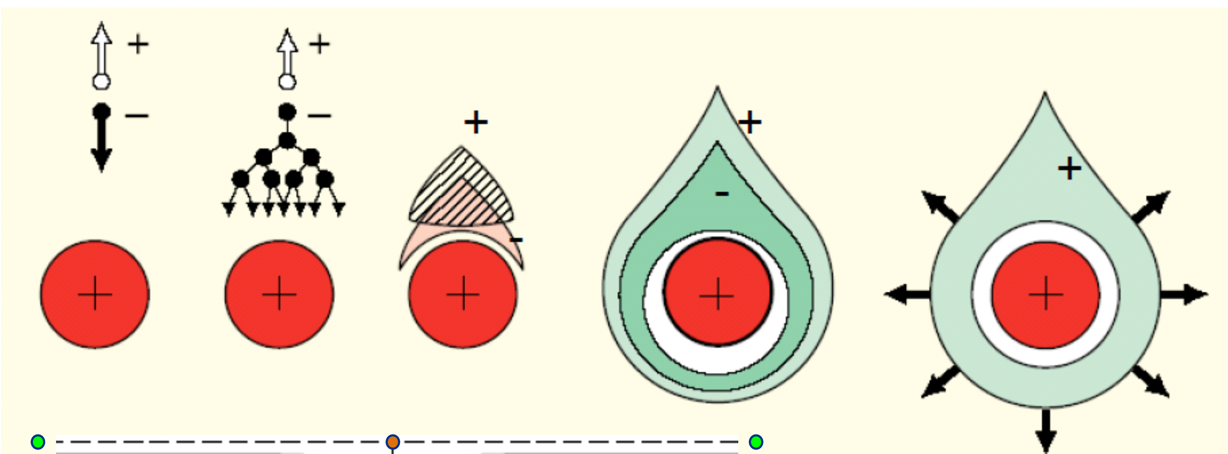
Tracking Detectors

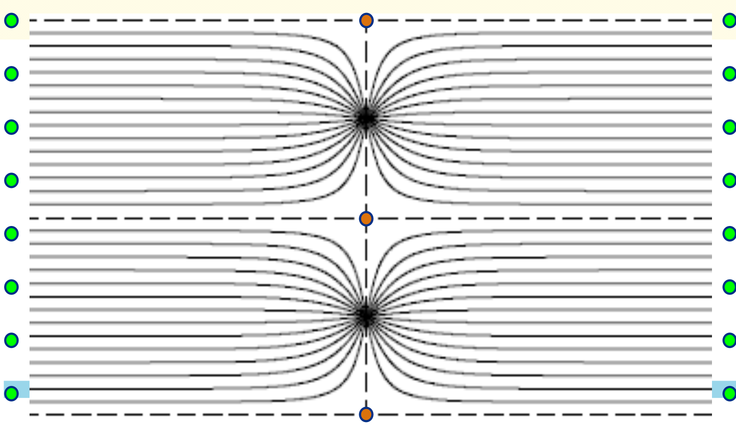
- Used for:
  - momentum measurements, charge determination
  - particle production position (primary and secondary)
- What are trackers made out of?
  - Gaseous detectors (Drift chambers, straws)
  - Solid state (silicon detectors)
  - Scintillating (fiber trackers)
- What are the important concepts?
  - Energy loss
  - Resolution
  - Being in a magnetic field

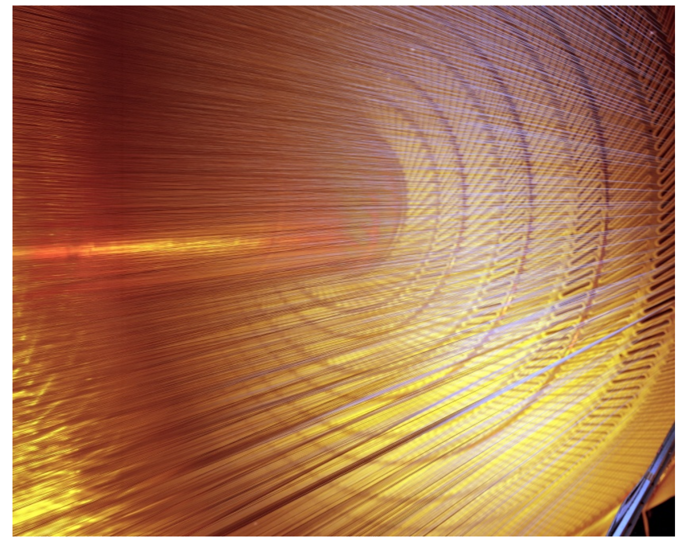


Gaseous Trackers

- Straws, Proportional Chambers, Drift chambers, GEMS, TPCs, etc
- Operate with high voltage, cathode/anode geometry, charge multiplication

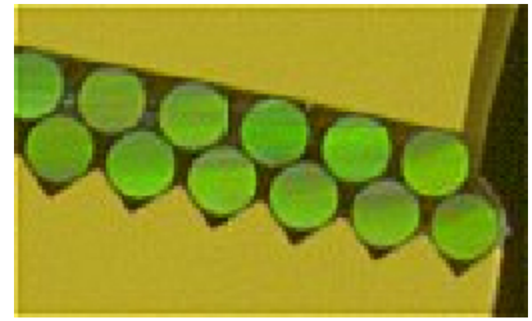






Solid State Detectors and Fibers

- Vertex detectors, microstrips, pixel detectors, fibers
  - Radiation hard (very important!)
- Silicon detectors have many nice features
  - Commerically produced
  - Can make fine granularity



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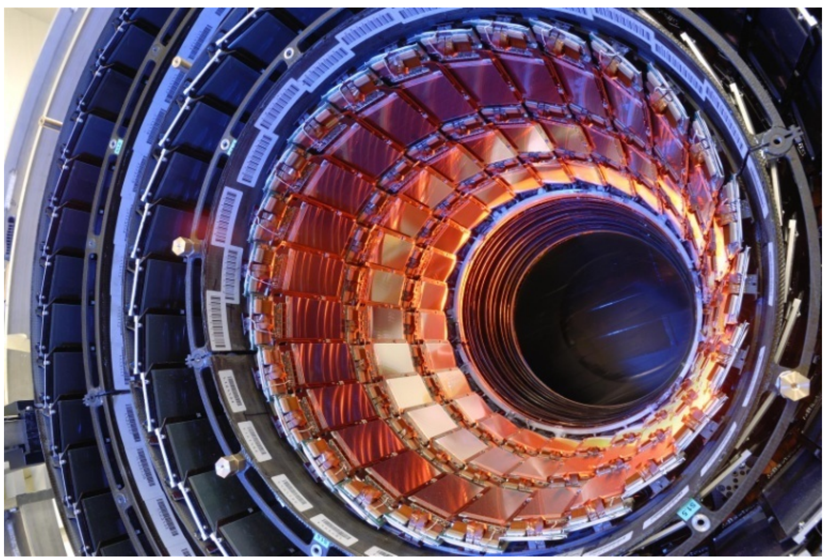


Bethe-Bloch Equation – Energy loss for "heavy particles"

- Relativistic Formula: Bethe (1932), others added more corrections later
- Gives "stopping power" (energy loss = dE/dx) for charged particles passing through material:

$$-\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

where

A, Z: atomic mass and atomic number of absorber

z: charge of incident particle

β,γ : relativistic velocity, relativistic factor of incident particle

$\delta(\beta\gamma)$: density correction due to relativistic compression of absorber

I: ionization potential

T_{max}: maximum energy loss in a single collision;

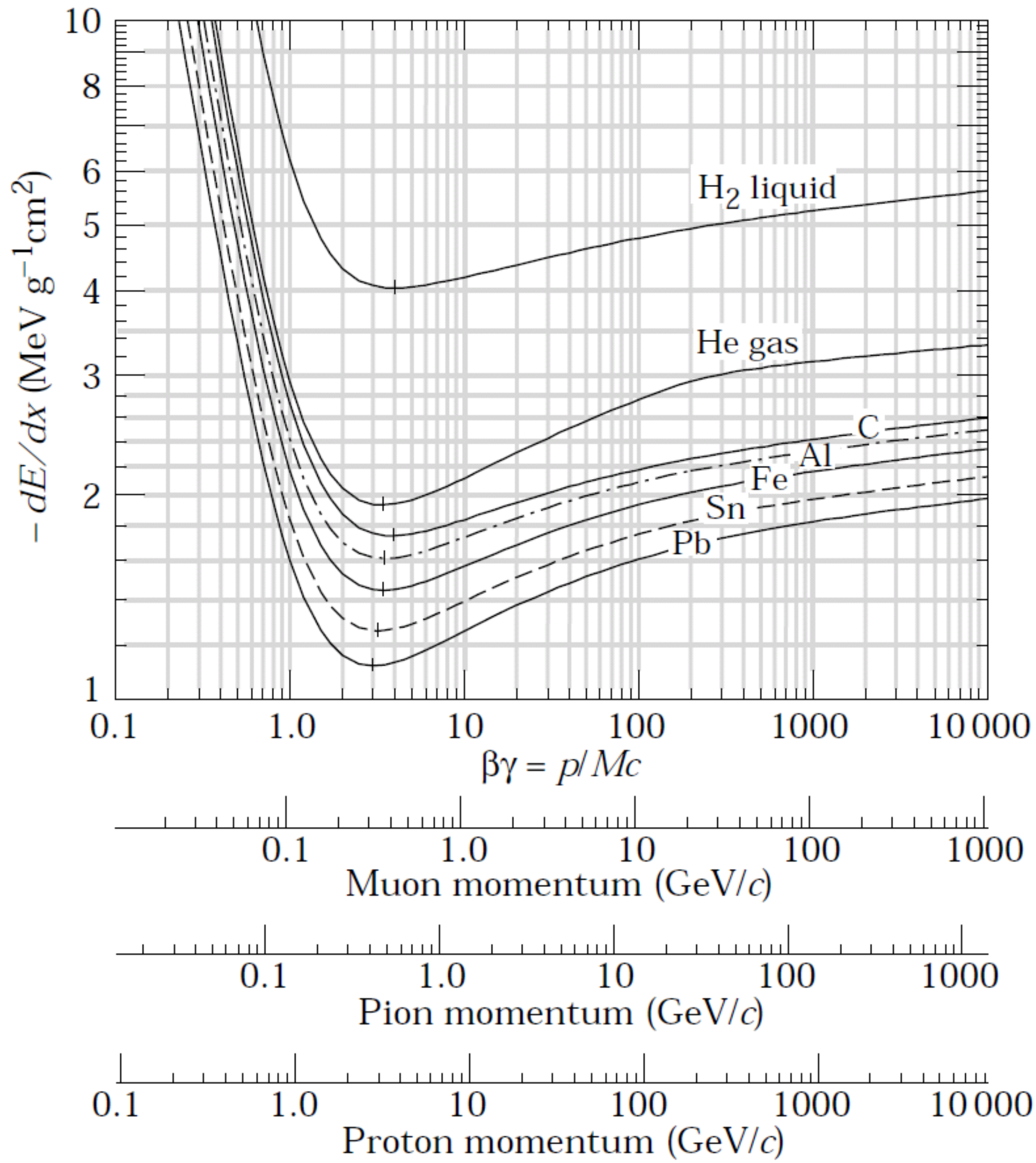
dE/dx has units of MeV cm^2/g

x is ρs, where ρ is the material density, s is the pathlength

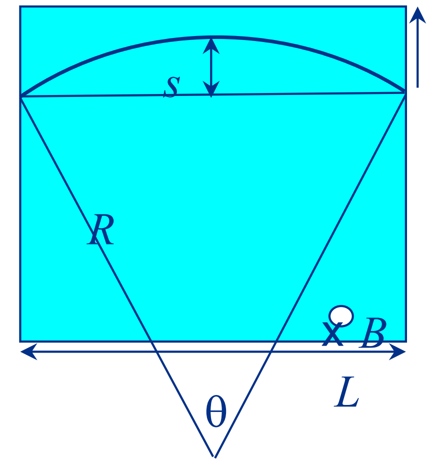
****Note that this is NOT for electrons, that requires more math****

Minimum Ionizing Particles

- Bethe-Bloch has same shape regardless of material
- The minimum is about the same regardless of material: occurs around $p/Mc = 3\text{-}3.5$
- dE/dx can be used to identify particle type along with an energy or momentum measurement



Resolution – How good is your tracker?



- Note that most trackers are in a magnetic field
  - p_T (Gev/c) = 0.3 B R
  - How well can we measure R?

$$s = R\left(1-\cos\frac{\theta}{2}\right) \approx R\left(1-(1-\frac{\theta^2}{8})\right) = R\frac{\theta^2}{8} \approx \frac{0.3BL^2}{8p_T}$$

- Depends on a variety of things, including the magnetic field
  - For three hits in a tracker:

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma_s}{s} = \frac{\sigma_x}{s}\sqrt{3/2} = \frac{\sigma_x \cdot p_T}{0.3 \cdot BL^2}\sqrt{96}$$

  - Note this equation improves with length squared and improves with magnetic field. It degrades with position resolution and the momentum
  - A rough estimate of how well we can measure resolution: $\dfrac{\sigma(p_T)}{p_T^2}$

Tracking Summary

- Three types of tracking detectors: gaseous, solid state, scintillating
- Gaseous detectors rely on charge multiplication
  - Gas choice is a bit of “magic”
  - Covers large areas ”cheaply” with sensitive materials
- Solid state/scintillating
  - Fine granularity, commercially produced
  - Can have problems with too much material in the beamline

Calorimeters

- Used for energy and mass measurements
  - Destructive (mostly) measurements
  - Point is to force particles to lose energy
- Comes in 2 flavors
  - Electromagnetic
  - Hadronic
- Either sampling or homogeneous
  - Many different material choices

EM Calorimetry

- EM calorimeters measure response from coulomb interactions (EM force)
  – Used to determine photons and electrons
  – Hadronic showers also have an EM component

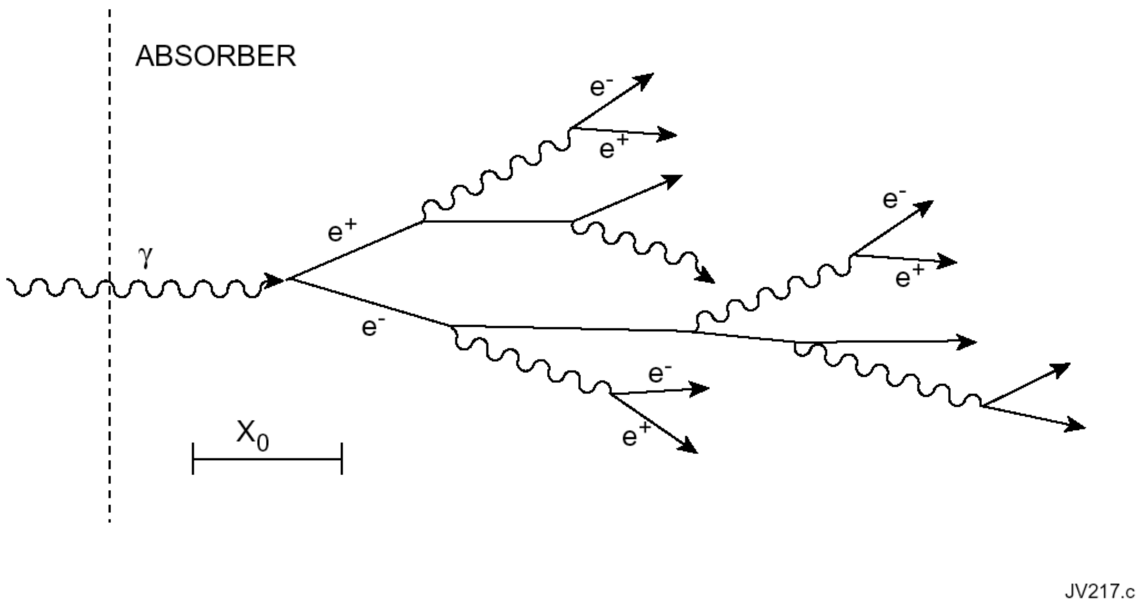
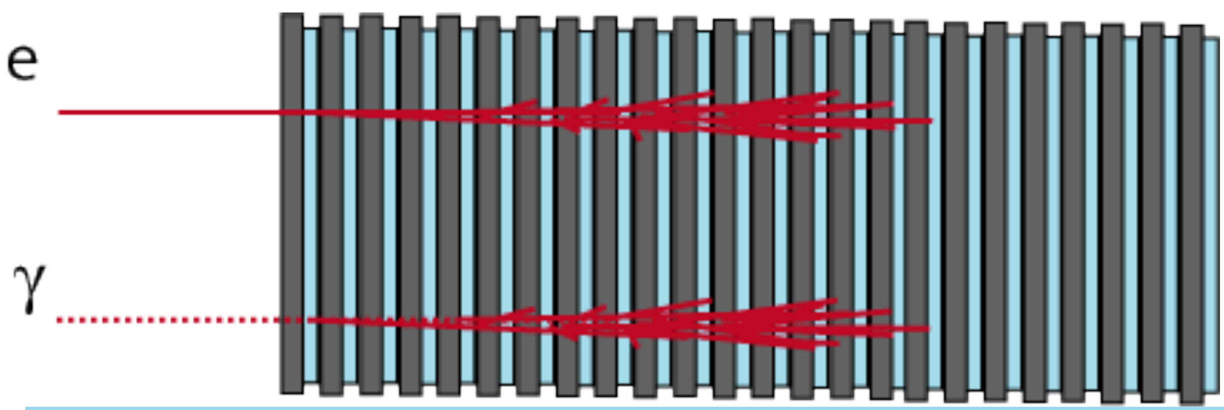


Figure 5: Schematic development of an electromagnetic shower.

EMCal: Definitions of Important parameters

- Radiation length: When a particle's energy is reduced to 1/e. This is how we describe the thickness of an EMCal:
  - $X_0 = 180\ (A/\ Z^2)\ (g/cm^2)$
- Critical energy: When the loss of energy from Bremsstrahlung equals the ionization loss of Energy: $E_c = 800/(Z + 1.2)$ (MeV)
- Moliere radius: Contains 90% of the shower and characterizes the width of the shower
  - $r = 21.2\ (\mathrm{MeV})\ X_0/E_c$
- Max shower: $S_{max\ =}\ \ln(E_{incoming}/E_c)$



Hadronic Calorimetry

- Hadronic calorimeters
  - Contain both an EM component driven by EM interactions and a hadronic component driven by Strong interactions

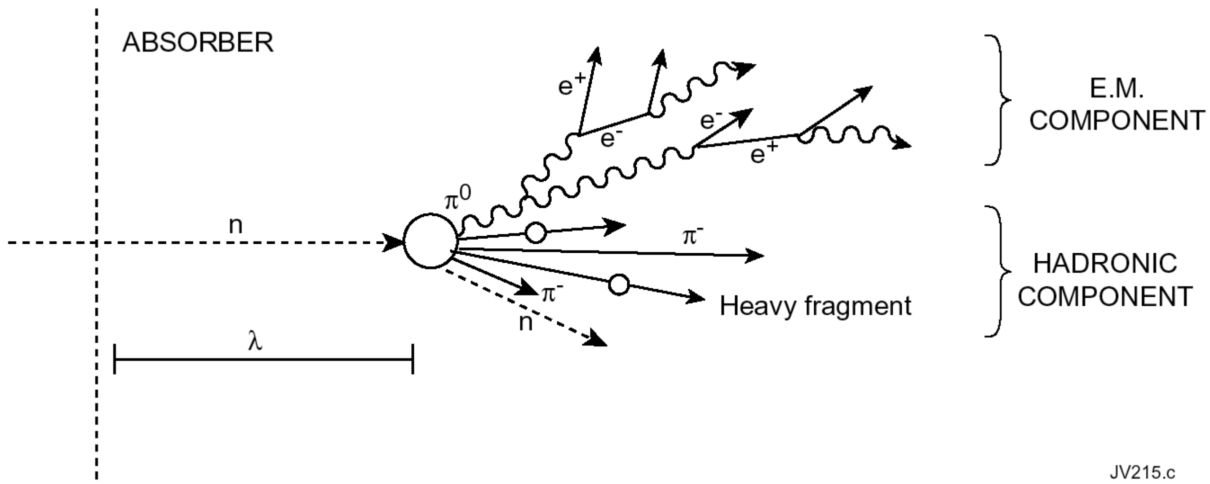


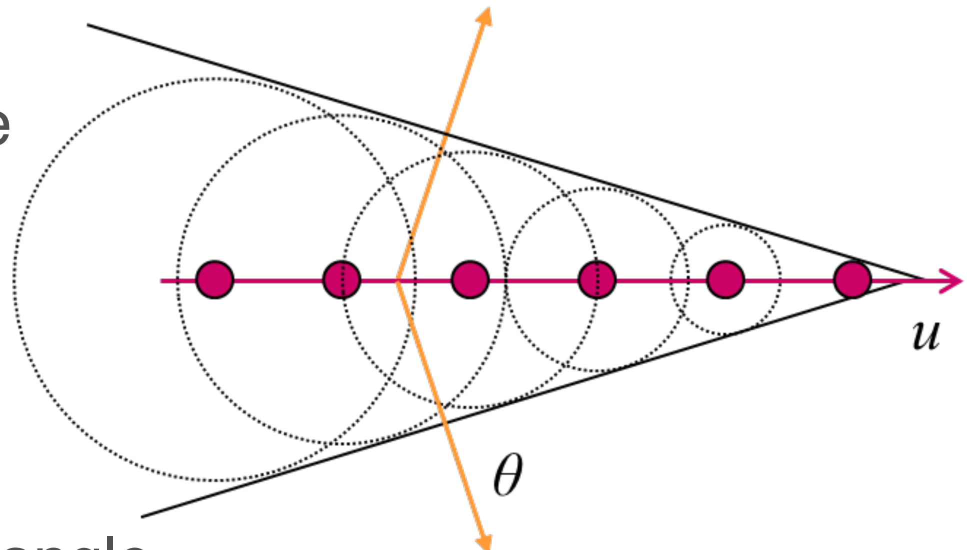
Figure 12: Schematic of development of hadronic showers.

HCal: Definitions of Parameters

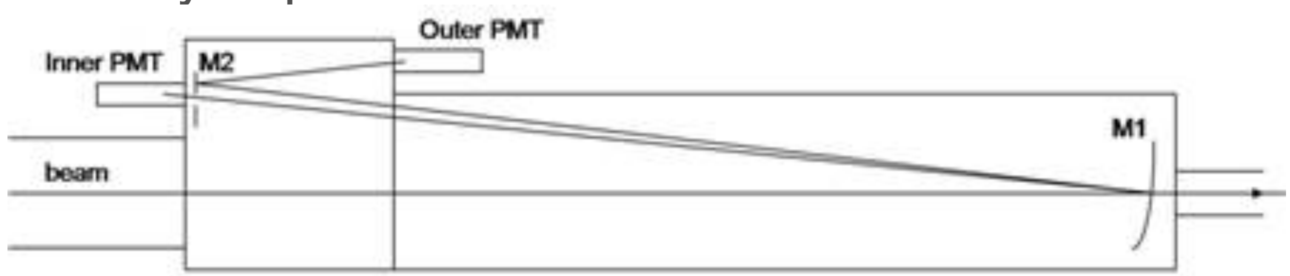
- Defined by nuclear interaction lengths instead of radiation lengths
  - Lambda = A / (cross section)*Number of atoms
- Much more complicated, no easy formulas to use to define various concepts (shower max, etc)
- Several orders of magnitude bigger than EM interactions
  - Might need 25 cm to contain an EM shower, but need 2.5 meters to contain Hadronic shower

Cherenkov Detectors

- In some materials, particles will travel faster than the speed of light
  - "Sonic boom" or a boat in the water

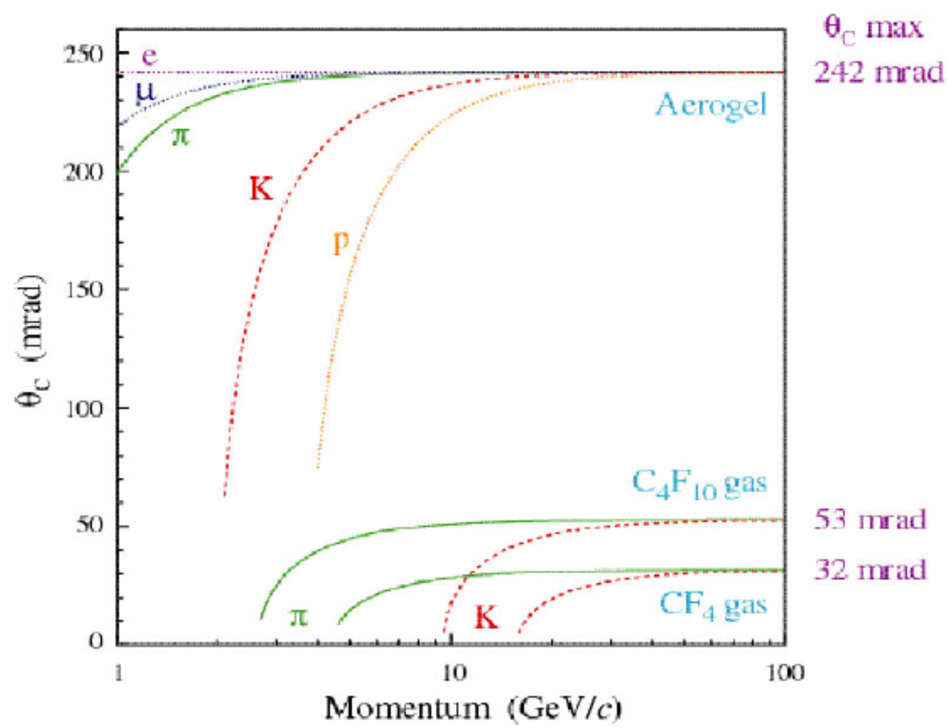


  - Main parameter: Cherenkov angle
    - Cos(theta) = 1/(n*beta)
    - Dependent of velocity of particle and the index of refraction for the material



Cherenkov and Transition Radiation detectors

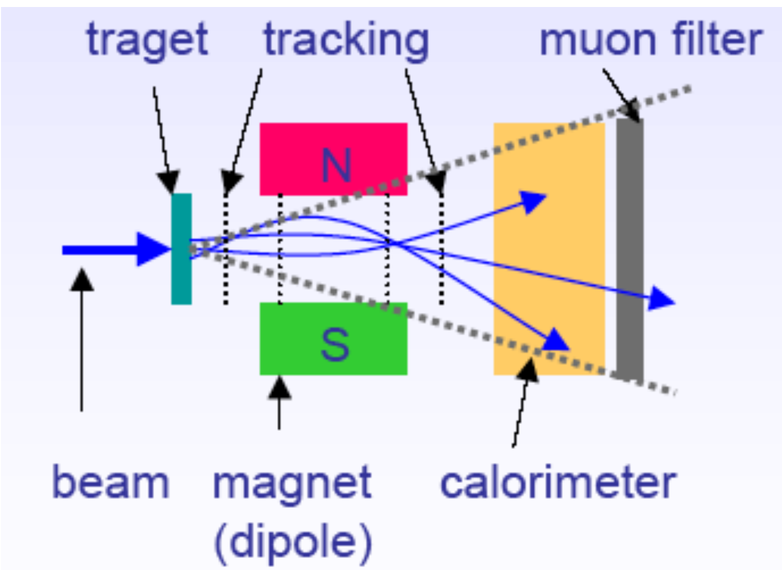
- Both used for Time of Flight and particle identification
  - Depending on mass and speed of particle, it will arrive in different places
- Important piece of the whole detector



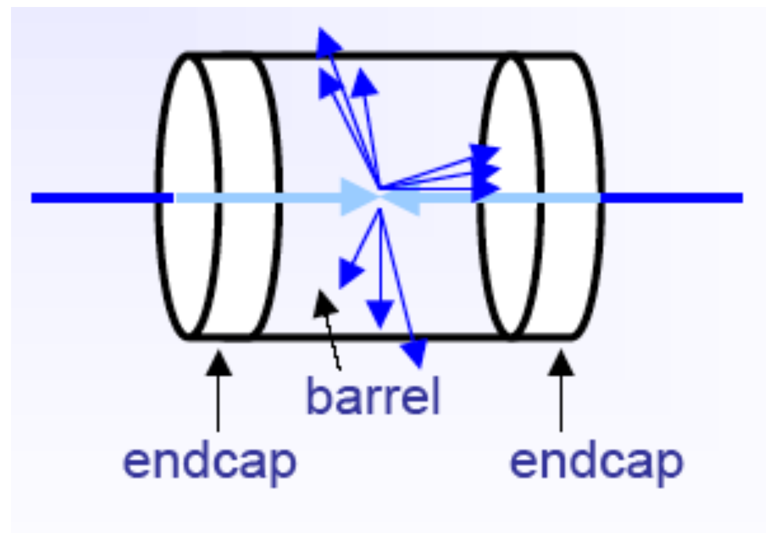
Putting it all together

- In order to fully understand an interaction, we should use multiple detectors. There are 2 classic geometries: fixed target and collider.

Fixed Target Geometry

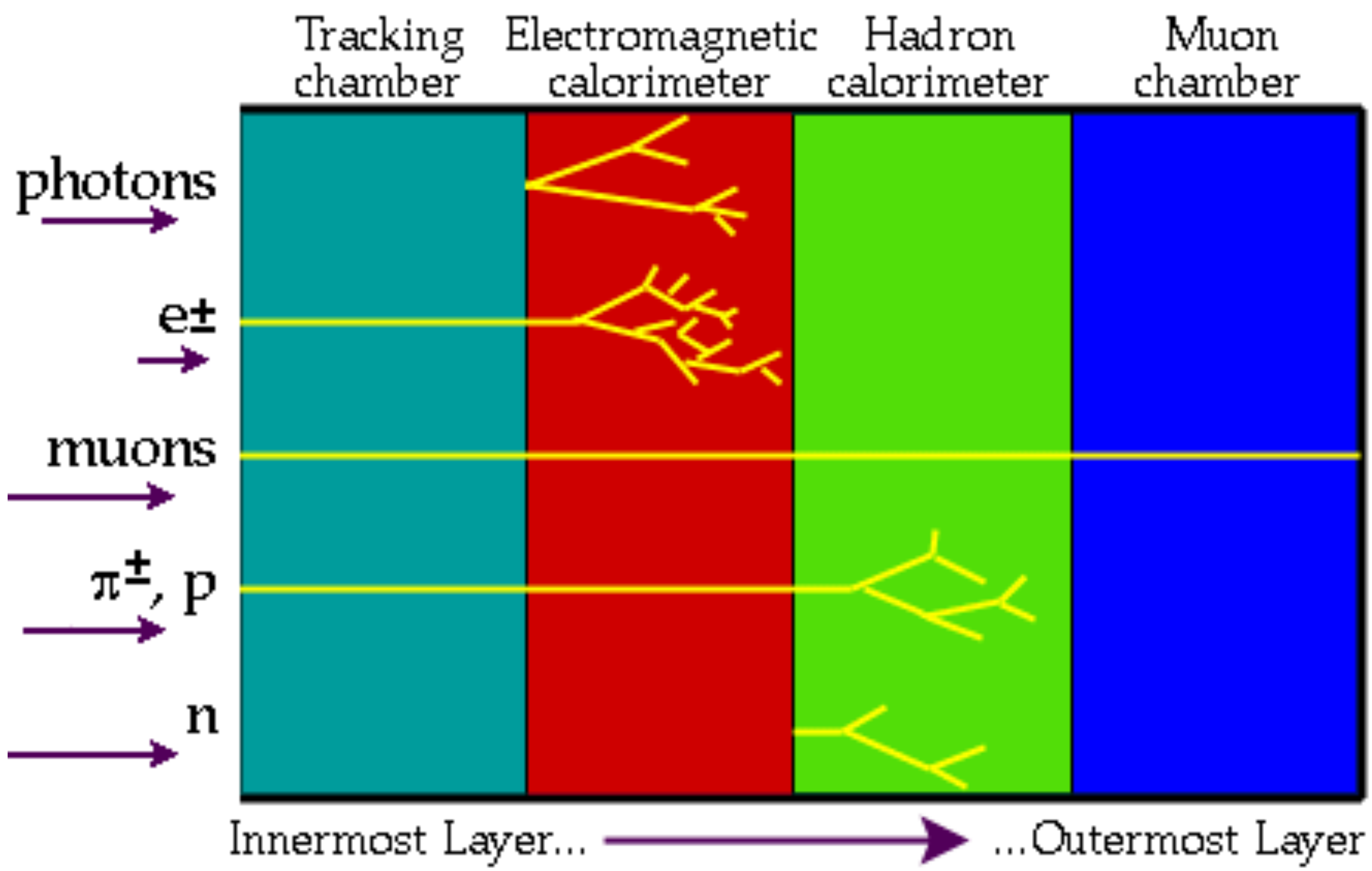


Collider Geometry



What do events look like?

- We can use the different detectors to figure out the signals



More information on what they look like

Signature	Detector Type	Particle
Jet of hadrons	Calorimeter	u, c, $t\rightarrow Wb$, d, s, b, g
'Missing' energy	Calorimeter	ν_e, ν_μ, ν_τ
Electromagnetic shower, X_o	EM Calorimeter	e, γ, $W\rightarrow e\nu$
Purely ionization interactions, dE/dx	Muon Absorber	μ, $\tau\rightarrow\mu\nu\nu$
Decays, $c\tau \geq 100\mu m$	Si tracking	c, b, τ

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Summary

- The physics of particle detectors comes down to matter interacting with matter
  – Could spend a lifetime studying these different effects
- What I want you to remember:
  – Charged particle interactions are our main source of information
  – Use energy loss to determine what type of particles you are dealing with
- Things not touched on at all
  – Readout electronics: extremely important!!!
  – Services: HV and gases, etc: also extremely important!!!
- This is an active field

References

- Interesting Lecture notes:
  - physics.ucdavis.edu/Classes/Physics252b/Lectures/252b_lecture3.ppt
  - http://www.desy.de/~garutti/LECTURES/ParticleDetectorSS12/Lectures_SS2012.htm
- Books
  - Dan Green's "Physics of Particle Detectors"
  - Any of the CERN Yellow books on detectors (particularly anything by Sauli) http://cds.cern.ch/collection/CERN%20Yellow%20Reports?ln=en